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Water Use Patterns: Examining the Impact of Population Density on Municipal Drought Response

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Water Use Patterns: Examining the Impact of Population Density on Municipal Drought Response

by

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Abstract

Water Use Patterns: Examining the Impact of Population Density on Municipal Drought Response

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Texas is urbanizing at a rapid rate with municipal water needs constituting a growing portion of total demand on the state's resources in the next fifty years. Geographic challenges contributing to frequent, severe droughts have driven a long history of water planning to balance these competing demands with unpredictable supplies. This report seeks to examine patterns in municipal water use to identify whether increasing population density impacts responses to drought conditions. It details the historical impact of drought on Texas water law and Texas' historical use of water in municipal settings, discussing historical and recent trends. Shifts in population from majority rural to majority urban are examined to identify whether behavioral responses to drought differ between urban and rural populations. This is done through the creation of a water demand regression model containing variables such as water price, rainfall totals, drought conditions, population density, median income, and per capita water use for five

Texas cities over twenty years. Ultimately, this analysis concludes that much of the variation in per capita water use was due to changes in time, although water price, rainfall, and population density were significant variables. As water use data collection improves and is conducted on an ever-more individualized scale, future analyses may identify a stronger relationship between population density and drought response.

Table of Contents

List of Tables

List of Figures

Chapter 1: Historical Water Use in Texas

Water is essential for life. It is present in every facet of human existence: to drink, to clean, to grow and prepare food, and to dispose of waste. It is therefore unremarkable that ancient human civilizations tended to locate in close proximity to clean, abundant surface water sources in order to thrive. This was true of the earliest residents of Texas as well. Many who immigrated to the state chose land located near a surface water resource and found supplemental sources underground.

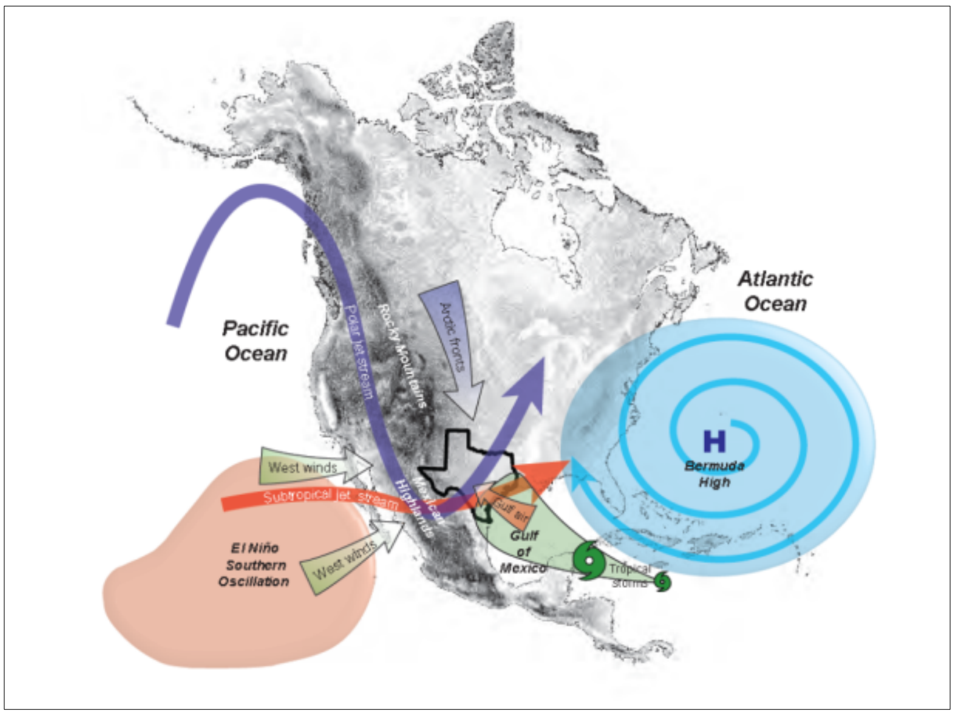
The availability of reliable water spurred the growth of Texas communities. Early Texans settled and gathered together where this basic necessity could be provided in a stable way. They developed civil and social infrastructure, built industry, grew crops, raised livestock, and ultimately made Texas what it is today. These early Texas settlers also witnessed a harsh reality of water: when it dries up, so does everything else.

How Texans have used this precious resource in their communities is a key part of the story of Texas itself. Our relationship to our environment, our land management practices, our economy and growth, and our health and wellbeing are all direct reflections of our water. This report seeks to examine how that relationship has changed in recent decades, particularly in times of water scarcity, as Texas' population density increased.

Geographic Challenges

Texas' unique geographic location has contributed to significant planning challenges for water use over its history. Positioned at the crossroads of multiple meteorological phenomena, the state witnesses frequent extreme weather conditions ranging from droughts, floods, tornados, severe thunderstorms, and hurricanes. The polar and subtropical jet streams, westward winds due to El Niño, high pressure to the east, and hurricanes from the Gulf of Mexico all influence Texas' weather patterns and water availability, as shown in Figure 1.

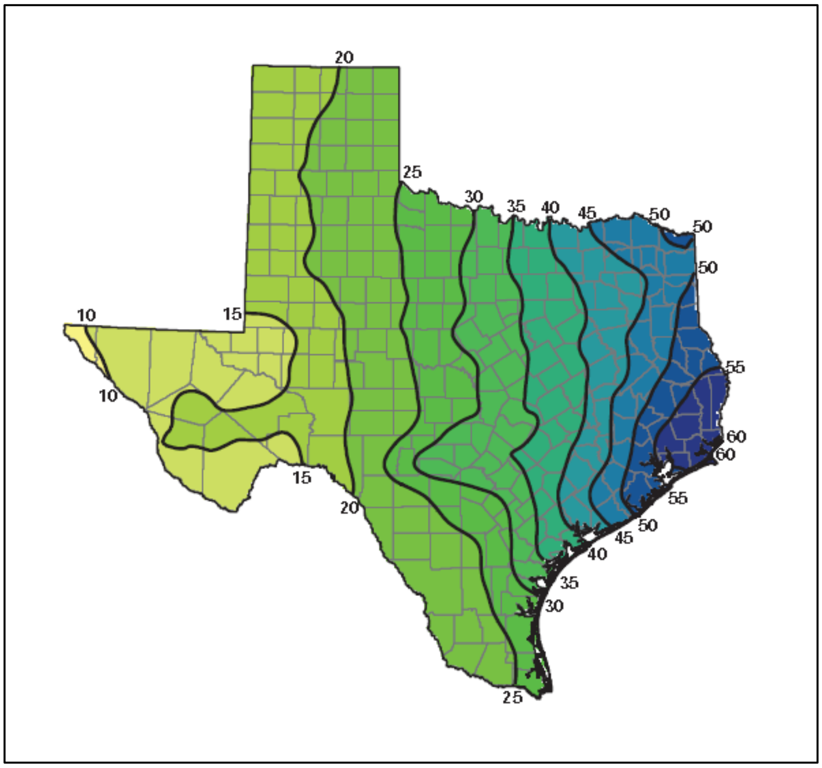
Figure 1: Geographic Location of Texas within North America[1]



Source: TWDB

With so much land area covered by the state, Texas also witnesses vastly different weather patterns and conditions from east to west and north to south. East Texas enjoys heavy precipitation levels and abundant surface and groundwater resources, but the western parts of the state see very little annual rainfall (as seen in Figure 2).[2] This unique situation means that variable weather is a part of life in Texas, leading many residents to note that if the weather is not to their liking, they need only wait a few minutes for it to change.

Figure 2: Average Annual Precipitation 1981 to 2010 (in inches)[3]



Source: TWDB

Even amongst this variability, several key themes (or maxims) can aid in understanding the impact of the weather on the state's water. These are outlined in Table 1. Each of these maxims aid in explaining a climate whose most predictable feature is its unpredictability. Precipitation levels and river flow in Texas decline steadily from the east to west across the state, and that precipitation mostly consists of rainfall due to deep convection. At both the state and regional levels (excepting the humid eastern side of the state), there is a near-balance between the precipitation that falls to the land and the evapotranspiration that whisks it away. Also, as Texas has increasingly overdrawn groundwater sources, the water supply paradigm has involved a shift to surface water resources.[4] Indeed, each of these themes related to water in Texas indicates that planning for use in spite of the variability in the water is difficult.

Table 1: The Five Maxims of Texas Water[5]

Maxim 1	Precipitation and river flow decline markedly from east to west across the state.
Maxim 2	Precipitation is almost entirely rainfall derived from deep convection.
Maxim 3	On both a statewide and regional basis, apart from the extreme humid eastern section of the state, there is a near balance between precipitation at the land surface and evapotranspiration.
Maxim 4	Rainfall and runoff are subject to long-period vacillations.
Maxim 5	The water supply paradigm is an increasing overdraft of a groundwater source followed by a shift to surface water.

Source: Ward, George H.

These maxims also serve to underscore a significant problem in Texas; when there is little rainfall, the state experiences harsh periods of drought. As we exhaust groundwater sources, which can occur more rapidly in drought conditions, we shift to surface water sources; as competition for these dwindling sources increases, so do debates about water rights and the priority of uses. Thus, many of Texas' changes in regulation through legal means have been in reaction to these extreme variations, and the development of water laws in response to drought conditions are a large part of Texas' water use story.

IMPACT OF DROUGHT ON WATER LAW

The unique weather variations that result from Texas' geography have been accompanied by a host of historical problems for Texas' residents. The boom and bust cycle of flood and drought in Texas means that there are seldom periods where the state does not see one of those extremes. Thus, many of Texas' changes in regulation of water use through legal means have been in reaction to this phenomenon. Drought response has been a driving force behind water governance in the state and is therefore a large part of our water use history. Table 2 provides a glimpse of how water law has changed in response to drought.

Table 2: Drought and Changes in Texas Water Laws[6]

Drought	Texas Water Law Change
1856	Creation of state geological survey for scientific recommendations on soil utilization and water resources; never completed due to civil war
1886-1887	• Creation of second state geological survey—completed for artesian wells – proposed new reservoirs built by convict labor • Introduced prior appropriation priority system for surface water rights
1901	Led to the groundwater Rule of Capture (East Case)
1909-1912	Creation of the Texas Board of Water Engineers and centralization of water rights claims

Table 2: Drought and Changes in Texas Water Laws, Cont.

1916-1918	• Led to the Conservation Agreement • Allowed legislature to create governmental entities to develop water resources and build dams and delivery systems—conservation and reclamation districts • Declared water resources public rights and duties • Vested water rights acquired prior to the act • Led to the establishment of special purpose districts called river authorities; Brazos River Authority in 1929, Guadalupe Blanco River Authority in 1933, and Lower Colorado River Authority in 1934
1933-1934	• The Dust Bowl; led to eventual creation of groundwater conservation districts – legislation to regulate groundwater failed in 1937 • Board of Water Engineers in 1938 called for state ownership of groundwater • Legislation to regulate groundwater failed in 1941 and 1947 • Legislation allowing for the creation of groundwater conservation districts passed in 1949 – first district created in 1951 (Martin County Underground Water Conservation District #1) • Wagstaff Act – (partially repealed in 1997) provided protection to upstream municipal water suppliers – provided that new appropriations would be granted subject to the right of municipalities to make further appropriations without necessity of condemnation (never used)
1950s	• Led to the creation of the Texas Water Development Board (TWDB) in 1957 • Led to a fivefold increase in groundwater pumping primarily for agriculture • Led to the *Valley Water* case settling claims for water on the Rio Grande below Falcon Reservoir and creating a new priority system for the lower Rio Grande based on type of use and established the first Watermaster program • Led to the Water Rights Adjudication Act of 1967 • Led to the construction of 23 major reservoirs in the 1950s (5.9 million acre-feet) and 34 more in the 1960s (14.3 million acre-feet) • Led to a water plan in 1968 that proposed bringing the Mississippi River to Texas

Table 2: Drought and Changes in Texas Water Laws, Cont.

1996	• Led to passage of Senate Bill (SB)-1 in 1997 establishing regional water planning • Created the *Junior Provision* for inter-basin transfers of surface water • Repealed parts of the Wagstaff Act and in its place established an emergency authorization provision for municipal water rights in the Texas Water Code • Under SB-2 (2001) the Texas Water Advisory Council was created; TWDB was required to develop Groundwater Availability Models; required water plans to include conservation and drought management practices; added language that Groundwater Conservation Districts are the state's preferred method of managing groundwater resources; charged TWDB with designating Groundwater Management Areas; and created the Water Infrastructure and Rural Water Assistance Funds • SB-3 (2007) established the process for environmental flow standards for new water rights permits
2009	Provided new authority to the Texas Commission on Environmental Quality on how to manage shortages of surface water and senior priority calls
2011	Led to House Bill (HB) 4, which established the State Water Implementation Fund for Texas (SWIFT) and restructured TWDB

Source: Rubinstein, Carlos

Comparing regulatory changes to drought periods highlights the reactionary nature of water policy in Texas; when there is a shortage of water, our laws change in order to try to meet ever-growing demand. Many of these changes over the history of Texas' water policy have dealt with providing for better long term planning for water resources or for gathering better data on water use patterns. Scarcity, in the case of water in Texas, drives innovation as well as monitoring of resources.

The increasing value of data collection related to water use can be observed in tracing the history of state agencies governing water use. The various organizations granted authority over appropriation, monitoring, and permitting of water use in the state have collected data in order to better understand how to cope. Data collection and analysis has increased significantly both in quality and quantity since the Board of Water Engineers was first created to oversee appropriations of water in 1913, but some form of water survey has been conducted since that date.[7] That agency took on various names (including the Texas Water Commission, The Texas Water Rights Commission, and The Texas Department of Water Resources) and functions over the elapsed time to present, but each of these water agencies has aimed to collect data on water use to inform planning for state resources. The current survey has remained fairly constant since 1985, and responses became mandatory for users of water for industrial, mining, and municipal purposes in 1999. Use for irrigation and livestock purposes are estimated based on secondary information sources. The annual survey covers the amount of water intake, the source of water, and the amount of water that was sold by the user.[8] Today, the Texas Water Development Board, the agency tasked with financing, planning, and developing future water resources for Texas, makes this survey data publicly available online.

Chapter 2: Municipal Water Use

As early as the first decade of the 20th Century, water engineers in Texas noted the importance of municipal water supply for domestic consumption, stating that the use of water for municipal purposes is "the highest application that can be made of it...the greatest number of human lives is dependent upon domestic consumption."[9] During the early settlement of Texas, many settlers relied on rural water supplies from shallow personal wells.[10] As settlements grew and towns formed, the availability of surface water was a key driver of growth; many municipalities relied on rivers and streams for a steady supply of domestic consumption, supplemented by small-scale domestic groundwater wells.

As Texans settled the land and the number of structures built increased, responses to often heavy rainfall events also became a prominent issue for cities. Flash flooding occurrences led to attempts to prevent floods in order to minimize the loss of life and damage to property in increasingly urbanized areas. The monitoring of stream flows gained importance for municipal purposes in order to ensure the availability of domestic demands. Better understanding of stream flows through data gathering efforts of the state in partnership with the United States Geological Survey allowed Texans to increase their ability to adapt to weather extremes. This analysis was also needed for the purpose of design, financing, construction, operation, and administration of public water supplies.[11]

WATER STORAGE AND STUDY

The Board of Water Engineers encouraged the construction of large water projects in a report released in 1918, calling for assistance from Texans of means to help finance and seek out appropriate sites for dams and reservoirs.[12] So began the construction of public water storage and retention projects, with early assistance from private funding, in an attempt to introduce greater predictability of available water. The control of flows resulting from heavy rainfall events was a chance for municipalities to obtain additional water to fuel growth. By the 1920's, monitoring streams for the purpose of planning for flood events and the surveying of dam and reservoir sites to capture excess water was codified into law. With the partnership of the Water Resources Branch of United States Geological Survey, the Board of Water Engineers began consistent collection and reporting of stream flow data for tributaries of every watershed in Texas. This was made available for municipal planning use, and allowed local planners to examine the unique flow and run-off patterns in different areas of the state.[13]

EARLY POPULATION GROWTH

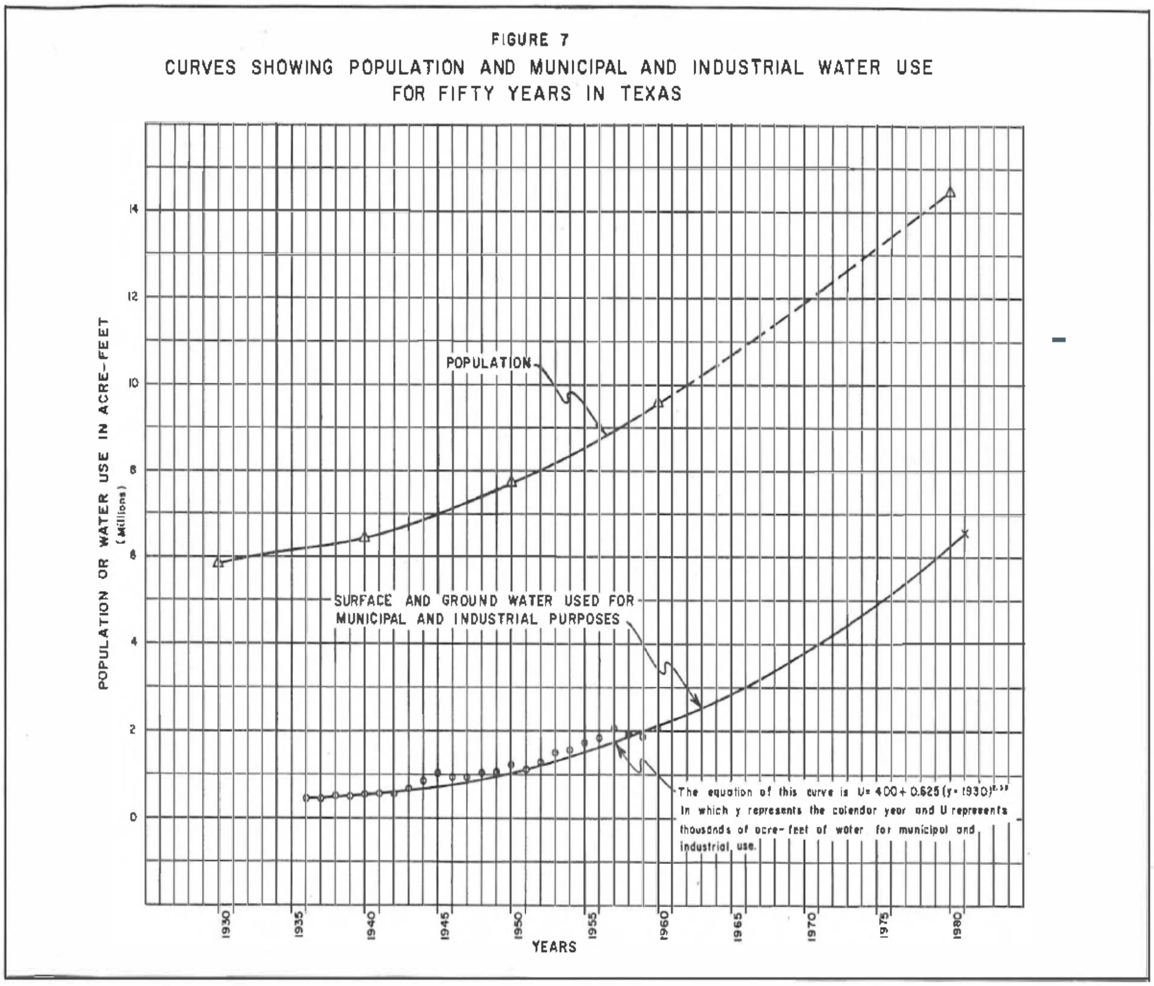
Even with the ability to capture and store excess water flow in reservoirs, the growth of municipalities stressed water supplies. By the late 1920's, the State was beginning to consider the possibility that Texans needed to look to underground water sources on a large scale. Reports from this era point out the Board's desire to explore and begin to plan for the use of groundwater sources:

> The Board is persuaded that some proper means should be provided by the Legislature for the investigation and control of sub-surface waters of the State. These waters constitute more than ninety percent of our total water supply, and in many cases will be the only source from which water may be secured artificially…the use of water from underground sources will largely increase at no distant day, and some means should be provided for regulating this use, and conserving, in so far as possible, this valuable resource.[14]

Legal and technological changes were also fueled in part due to population growth. Beginning in the 1930's, Texas statute identified municipal water use as a top use priority; in the Wagstaff Act of 1931, the 42nd Texas Legislature deemed that water appropriated for any other use could be taken by State permit for municipal or domestic purposes to sustain human life.[15] Technological developments paved the way for greater growth as groundwater well capacity and equipment efficiency increased. The development of groundwater became a significant force behind large-scale municipal growth statewide, but offered new opportunity to surface-water poor areas in particular. Texas' urban population began to climb; by 1930, 41 percent of the population was located in urban municipalities, and by 1960 that percentage had climbed to 75 percent. El Paso offers an example of this growth. The first municipal well, drilled in 1906, offered annual average pumping of about 19,000 acre-feet per year between 1936 and 1940; by the late 1950s, pumpage had increased to 87,000 acre-feet per year.[16]

Just as technological developments made urban population growth possible, urban population concentrations drove increases in municipal water requirements. Urban centers began to expand in the 1930's due in part to the migration of people to Texas from outside the state and in part to a shift from rural to urban life as new industry brought additional work to urban settings. Municipal water use planning became more complex, incorporating estimates of population trends and increases in daily per capita consumption. Texas' population growth increased at an increasing rate in the mid-20th century; the population grew by 590,109 people between 1930 and 1940, by 1,296,370 people between 1940 and 1950, and by nearly 2 million people between 1950 and 1960. Figure 3 details projected trends in industrial and municipal water use in Texas, as estimated in the 1961 State Water Plan.

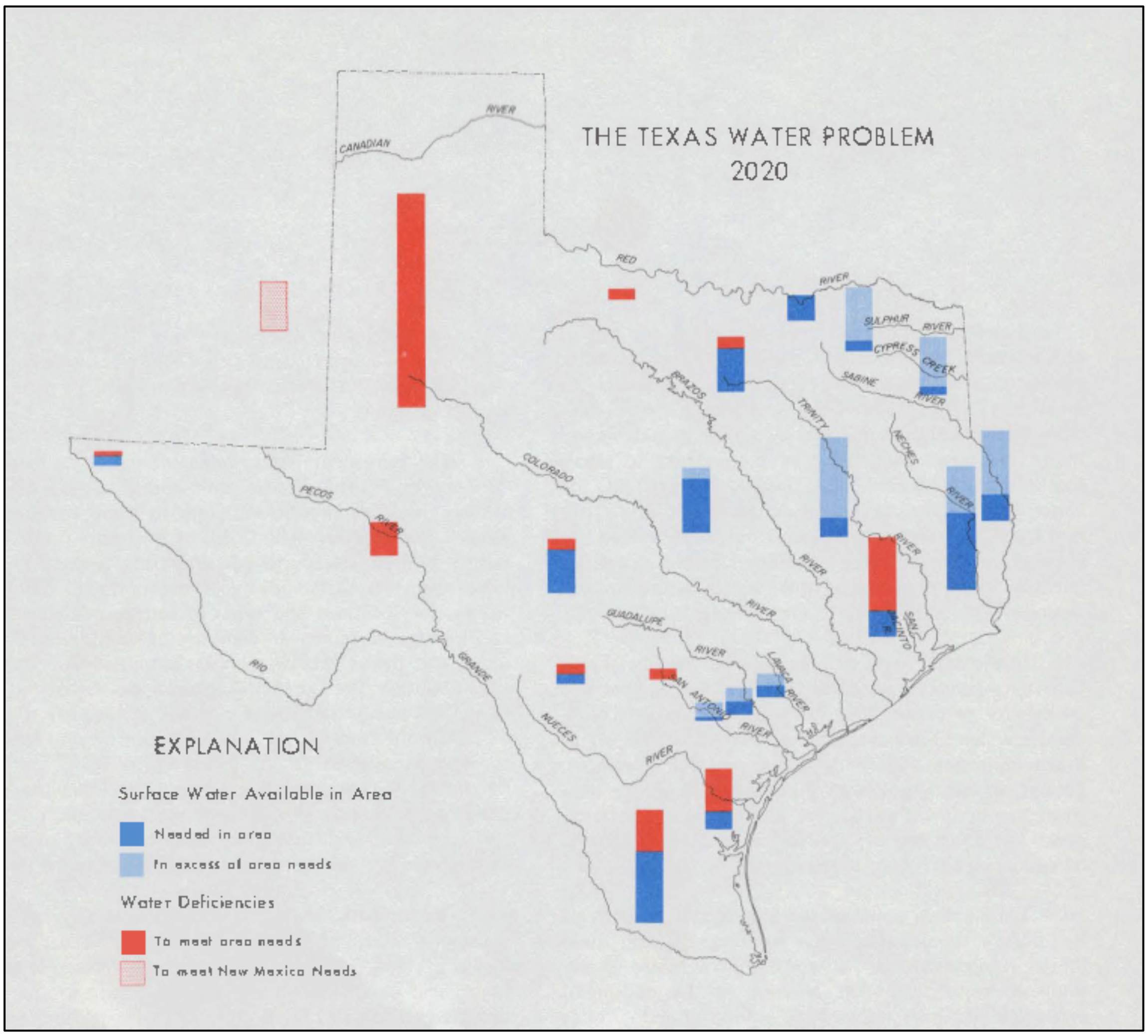
Figure 3: Curves Showing Population and Municipal and Industrial Water Use for Fifty Years in Texas[17]



Source: 1961 Texas State Water Plan

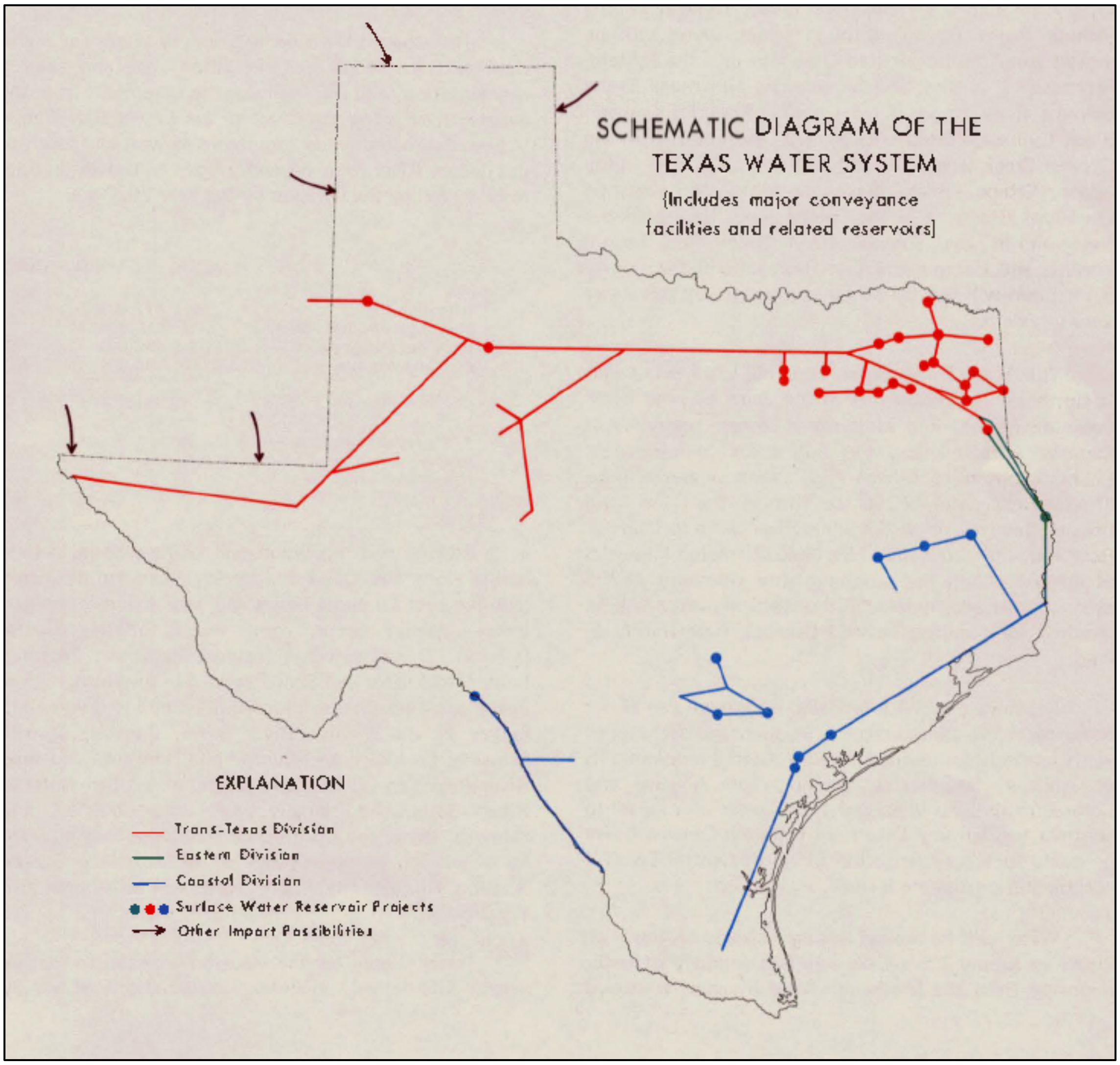
A few years later, the 1968 State Water Plan acknowledged the beginning of concerns over limits of water resources and the implications for water use; at that point in time, the bulk of remaining resources available for development lay in East Texas, but anticipated need centered in the drier west and southwest areas of the state. For the first time, Texas water planners seriously entertained strategies to import and pipe water across the state (from sources such as the Mississippi River) to supplement population growth. Figures 4 and 5 illustrate this conundrum, as well as the pipeline project proposed as a solution in 1968. Incidentally, this pipeline was never constructed. Similar proposals, however, resurfaced for debate in the 84th Texas Legislative session in 2015.

Figure 4: The Texas Water Problem 2020 (as estimated in 1968)[18]



Source: 1968 Texas State Water Plan

Figure 5: Schematic Diagram of the Proposed Texas Water System[19]



Source: 1968 Texas State Water Plan

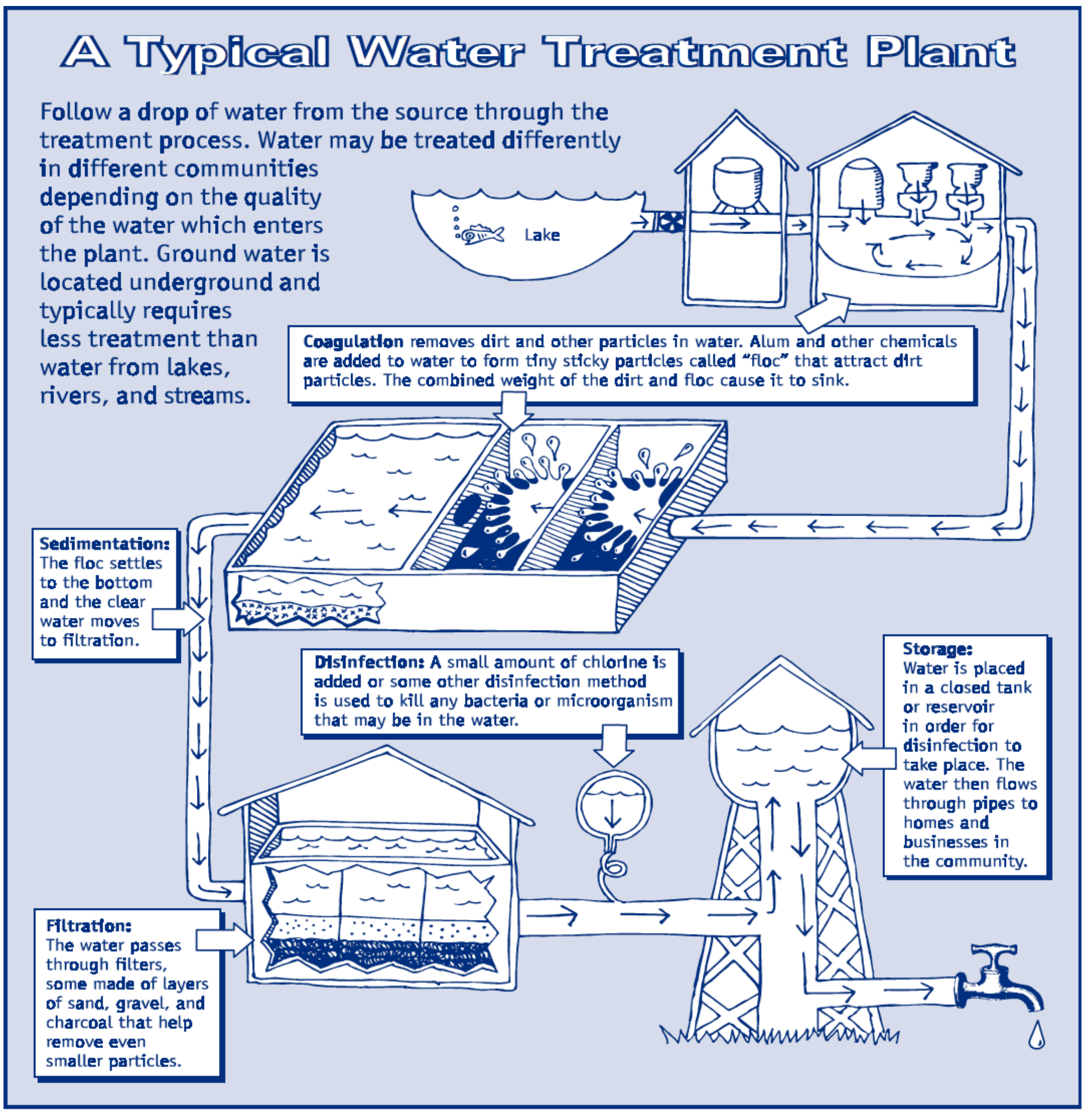
Water planning began to address the concern that Texas' existing water supplies would be insufficient to meet ever-growing population and competing water demands for municipal, industrial, and agricultural purposes. As Texas has grown in population and in diversity of economic sectors represented in the state, water planning has become both more challenging and more sophisticated – for municipal use, in particular.

REGULATION AND TREATMENT OF MUNICIPAL WATER

Human civilizations have always been concerned with water *quantity*, as demonstrated by the formation of communities in areas in proximity to water supplies. Understanding of water *quality* (beyond purely aesthetic characteristics such as smell and turbidity), however, has been a relatively recent development.[20] Much of the current regulatory structure protecting water quality in the United States is due to the nature of who traditionally provided public water. Since municipalities were often responsible for the bulk of drinking water provision, standards were developed in order to fulfill their duties to protect public health. Scientific understanding of water-borne diseases such as cholera and the development of germ theory in the latter part of the 19th Century provided a catalyst for developing these water regulatory systems to govern drinking water treatment.[21]

Federal regulation of drinking water quality dates back to the early 20th Century. In 1914, the U.S. Public Health Service began to regulate bacteria standards for drinking water to prevent the spread of disease. These standards were built upon regulating additional dissolved substances in water over time leading up to the passage of the Safe Drinking Water Act of 1974; these standards were adopted by all 50 states as guidelines for public water systems. Today, the Environmental Protection Agency's Office of Ground Water and Drinking Water administers this law,[22] and sophisticated filtration and chlorination techniques protect municipal systems from microbial pollutants. The Centers for Disease Control and Prevention and the National Academy of Engineering highlighted the importance of water treatment as "one of the most significant public health advancements of the 20th Century."[23] The ability to control the quality of water in municipal settings has been a crucial part of preventing the spread of widespread water-borne disease, allowing the increase of urbanization. Figure 6 provides a look at the steps taken to meet drinking water quality standards in a typical water treatment process.

Figure 6: Example Municipal Water Treatment Process[24]



Source: Environmental Protection Agency

MUNICIPAL WATER PROVISION

Each municipality supplies its water from various unique sources. Municipal water systems can draw water from surface sources such as rivers, lakes, and reservoirs, and from groundwater, or can import water if no other sources are available. Water is taken from its source and conveyed via pipes or canals to the water users, including agricultural, municipal, and industrial, and power generation customers.[25] Water sent to municipalities is then subjected to central treatment, usually at a water treatment plant, to meet standards for human consumption. Larger urban systems enjoy funding from larger customer bases, usually allowing for the installation and maintenance of more sophisticated treatment systems.[26] This potable water is then distributed from the treatment facility through networks of underground pipes to the end users.[27] This used water, or wastewater, is then collected, treated, and returned to a water source.

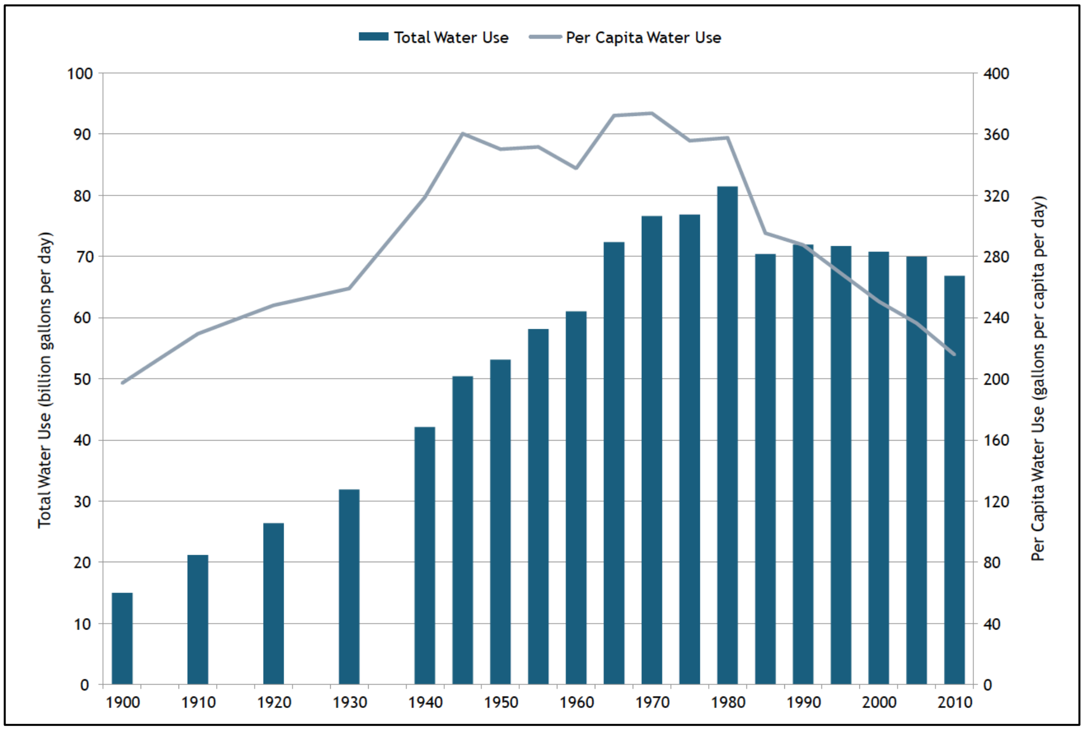
Today's system of urban infrastructure gives municipalities the ability to supply water to urban areas and remove both sewage and storm water for the protection of urban residents and local water supplies. These services are made possible by the man-made infrastructure of reservoirs, channels, canals, pipes, pumps, and treatment facilities, often owned by cities or water/sewer agencies. Water providers are faced with large capital investment costs to construct this infrastructure, and bill water users to cover this expense as well as the ongoing maintenance expenses over the lifetime of the system. Private companies operate some systems, but municipalities usually retain ownership of the infrastructure responsible for delivery of water to municipal customers.[28]

Though the construction of this municipal water infrastructure enables the provision of water for life in urban settings, manipulation of the land and water cycle is not without consequences. Diverting, storing, and capturing water disrupts the natural patterns and flow of water in any case, and the "creation and operation of urban water systems fundamentally changes the natural hydrologic flow across landscapes."[29] The construction of storage facilities and networks of pipes not only manipulates the flow of water, but also adds concrete cover to the land surface, which can ultimately inhibit the flow of groundwater into aquifer storage. Excess concrete also exacerbates flooding in urban areas, when water that would naturally drain is captured and trapped amidst urban dwellings and infrastructure. The more recent focus in engineering research on "green infrastructure" approaches to water, wastewater, and storm water management are an indication of both the significance of the problems created by these engineered structures and a turning point in addressing them.[30]

Nationwide Trends in Municipal Water Demand

Though historical estimates vary, nationwide demand for municipal water trended upward from 1900 until its peak in 1980. Reductions in per capita water use following 1980 were achieved due to shifts toward a less-water intensive, service industry economy coupled with policies that encouraged water efficiencies. These trends can be observed in Figure 7.

Figure 7: Total and Per Capita Water Use for Municipal/Industrial Sector (1900-2010)[31]



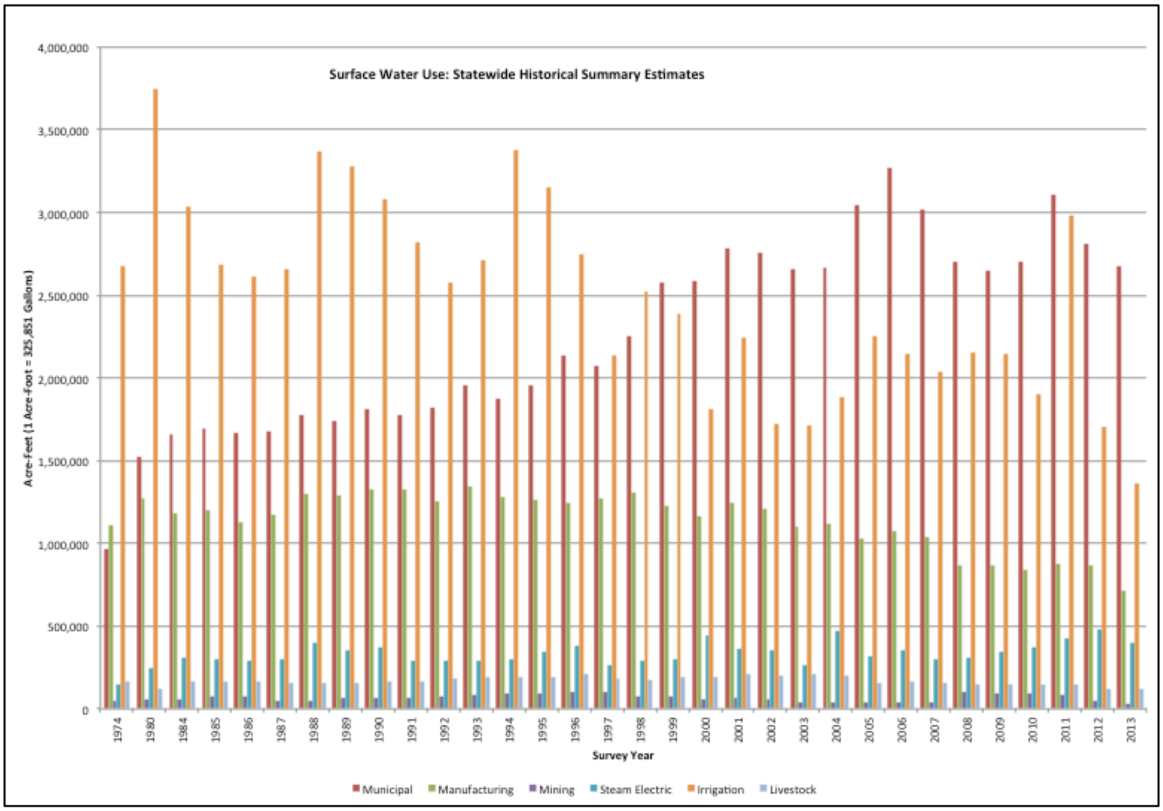
Source: Pacific Institute

The National Energy Policy Act of 1992 set efficiency standards for toilets, urinals, faucets, and showerheads, and later legislation included clothes and dishwashers and other commercial products.[32] Later, the Environmental Protection Agency developed its "WaterSense" Program, encouraging the labeling of appliances that surpass water efficiency standards, offering a similar model to the EnergyStar Program.[33] Greater efficiencies in water transfer and use in recent decades have enabled significant declines in per capita water demand since 1980, despite continued growth in population.[34]

Similar to national trends, per capita water use has declined in Texas in recent decades, likely due to the adoption of more efficient technologies. The installation of more water efficient plumbing pieces such as shower heads, toilets, and faucets was required by the Texas Water Saving Performance Standards for Plumbing Fixtures Act of 1991, and future decreases in water use are expected as additional old equipment requires replacement.[35]

TEXAS TRENDS IN MUNICIPAL WATER DEMAND

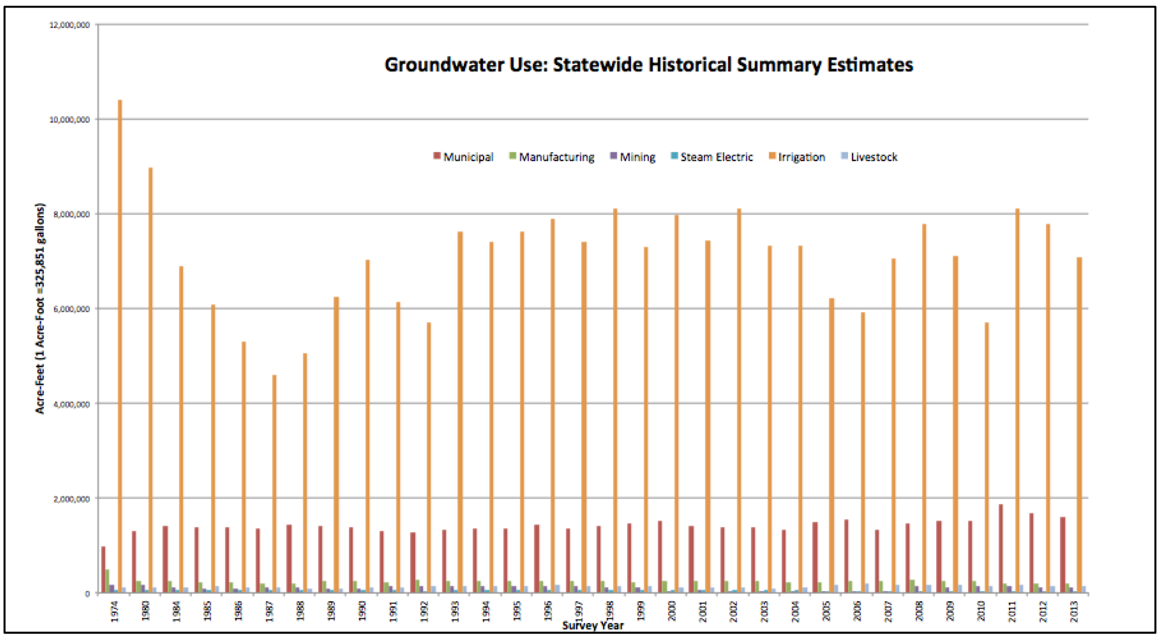
Figure 8: Texas Surface Water Usage by Sector



Source: Data from TWDB

Longitudinal data collected by the Texas Water Development Board offers a glimpse at total municipal water use in relation to use by other sectors. Municipal use of surface water, shown in Figure 8, rose through the 1970's and 1980's, surpassing irrigation totals beginning in the late 1990's. The shift from irrigation to municipal as the largest surface water user mirrors a growing statewide focus on shifts from primarily rural living to primarily urban population centers. The spike in municipal usage and a corresponding decline in water use for irrigation and manufacturing sectors also occurred, in part, due to the allowance of inter-basin transfers of water following the drought in 1996.[36]

Figure 9: Texas Groundwater Usage by Sector



Source: Data from TWDB

Municipal use of groundwater, by comparison, appears relatively constant. This is shown in Figure 9. Small cyclical upticks in usage, however, appear to correspond to periods of drought in Texas. This highlights the nature of a drought response trend: when drought occurs and surface water supplies face shortage, groundwater usage for municipal supply often increases.

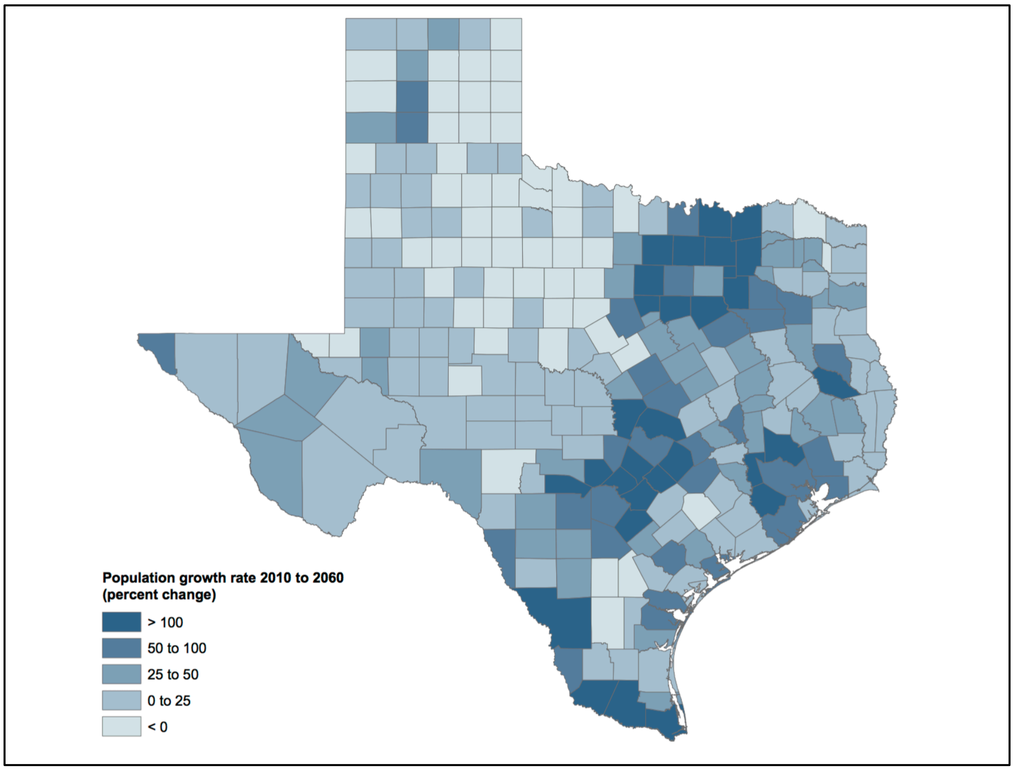
Chapter 3: Texas Demographics

CURRENT GROWTH CHALLENGES

Recent population growth has been dramatic in Texas, though uneven across the state, and demographers expect similar growth in the future. Between 2010 and 2060, Texas' population is expected to increase by 82 percent from 24.4 million to 46.3 million,[37] with much of that growth occurring in urban centers in the eastern half of the state and along the Interstate 35 corridor. Figure 10 highlights areas where higher growth rates are clustered. The Dallas-Fort Worth, San Antonio, Austin, Houston, and Rio Grande Valley Areas, as well as El Paso, can be seen as areas with the greatest expected growth rates to 2060.

In order to ensure adequate water provision for this influx of population, the Texas Water Development Board incorporates projected water demands into the regional and state water planning process to determine how much water would be required in times of drought. For these purposes, municipal water use refers to "residential, commercial, and institutional water users in (a) cities with more than 500 residents, (b) non-city utilities that provide more than 280 acre-feet a year (equivalent to 250,000 gallons per day), and (c) a combined water user grouping of each county's remaining rural areas, referred to as county-other."[38] Water demand projections for the municipal sector includes water used for both residential and commercial purposes (as well as some manufacturing that does not use water in the production process), and some institutional uses at public service-oriented establishments.[39]

Figure 10: Projected Population Growth in Texas Counties[40]



Source: TWDB

Though the overall population is expected to grow by 82 percent by 2060, water demands are projected to increase by only 22 percent.[41] State Water Planners indicate that this comparatively moderate projected increase is due to future decreases in irrigation use of water as well as increased conservation tactics by municipalities, actually resulting in a slight decrease in future municipal per capita water use. The Texas Water Development Board describes the method of estimating these projections in the following way:

> Municipal water demand projections are calculated using the projected populations for cities, non-city water utilities, and county-other and multiplying

the projected population by the total per capita water use. Per capita water use, measured in "gallons per capita per day," is intended to capture all residential, commercial, and institutional uses, including systems loss. Gallons per capita per day is calculated for each water user group by dividing total water use (intake minus sales to industry and other systems) by the population served. Total water use is derived from responses to TWDB's Water Use Survey, an annual survey of ground and surface water use by municipal and industrial entities within the state of Texas.[42]

RURAL TO URBAN POPULATION SHIFT & SCARCITY IMPLICATIONS

The major urban centers of present day Texas stand in stark contrast to the rural, open plains of the past, a trait that is reflected in water use patterns. Once dominated by an agricultural economy, expected decreases in water use for irrigation points out a deep shift underway in the state. Texas is becoming more urban, and rapidly so. Texas' State Demographer Lloyd Potter described growth and demographic trends in Texas in 2013 as "faster than anywhere else in the country," with major urban areas expanding in terms of numbers and in speed.[43]

This rapid shift from rural to urban settings has far reaching implications for the way Texans live and relate to our natural environment. This shift to primarily urban life also reflects a shift in mindset; as more people cluster in urban areas, the connection to the land becomes weaker.[44] Rural landowners can more easily observe weather and water patterns and direct impacts on their land. Because of this ability to see nature at work, they may have a greater opportunity to understand how their water use impacts water availability. Rural landowners often depend on private wells for domestic and livestock supplies of water, and are likely to understand the limits of their personal water source and storage capacity. If rainfall totals were low and drought was declared, the rural landowner was likely to see the direct impact of water scarcity in a tactile way, watching a stream or lake evaporate or a well run dry. The nature of this very visible environmental impact of drought, to the rural landowner, was likely followed by a shift in behavior. When we can see a lack of water as negatively impacting the availability of future water for daily activities, we are likely to begin to conserve the resource. With fewer and fewer Texans living in rural settings, however, this connection to the health and availability of water sources may be altered.

Many in urban settings struggle to identify where their water comes from, let alone identify characteristics related to the availability and sustainability of that water supply. Municipal residents, at no fault of their own, turn on a tap and water appears. If regular municipal supplies run low, municipal officials arrange for alternative supplies in order to maintain service. If not for drought declarations and city efforts to restrict usage in times of drought, urban residents would likely see little difference between times of plenty and times of water scarcity.

When cities that are reliant on surface water bodies for municipal supply face water scarcity, the natural shift is from surface to groundwater.[45] The passage of omnibus Senate Bill 1 by the Texas Legislature in 1997 allowed for inter-basin transfers and has implications for urban water provision as well. Inter-basin transfers are defined as the "taking or diverting of state water from a river basin and transferring such water to any other river basin."[46] The "junior rights" provision included in this bill serves to remove a senior water right in the event of an inter-basin transfer.[47] Thus, when water is offered for sale in a transfer, there develops a divide between the seller and buyer's estimates of worth. Water sold loses value in the seniority of the right.[48]

Though these transfers offer a way to redistribute state water to areas in shortage, this solution may not prove viable for municipal provision in times of drought. Many cities like Dallas depend on a majority of their water from inter-basin transfers; if the priority of that water is called into question, the provision of their water may hang in the balance. Case in point: The Dow Chemical Company's assertion of its senior water right to flows from the Brazos River beginning in 2009 resulted in the Texas Commission on Environmental Quality (TCEQ) curtailing water users upstream. In the interest of public health, TCEQ maintained water provision to municipal users despite their junior right status at that time. In February 2016, however, the Texas Supreme Court upheld a prior ruling that the state cannot prioritize cities or power generation over senior rights to water.[49] Thus, municipalities dependent upon these junior rights resulting from inter-basin transfers may be at a loss for water in times of scarcity.

Chapter 4: Analysis of Urban Impact on Municipal Per Capita Water Demand in Drought

THEORY

Though there is ample research on the value of water for rural and urban uses, there is comparatively little research to date on whether the behavior of water users in these contrasting settings has an impact on water use in times of scarcity. This analysis seeks to better understand this connection, examining the following question: as Texas has become more urban over the last two decades, what has happened to per capita water use? Since residents in urban areas have less direct connection to large parcels of land and to the sources of their water, does their response to drought vary from responses in rural areas? In other words, if we live in a more urban setting, do we cut back on our water consumption less than rural residents during a drought?

DATA AND MODEL DESCRIPTION

In order to examine these questions, I used STATA software to model and analyze per capita water use trends in five Texas cities that have experienced recent and rapid urban growth. The municipalities of Austin, Dallas, Houston, San Antonio, and El Paso were chosen because these areas have changed dramatically in percentage urban/rural over the last few decades, and necessary data could be obtained for these areas. In 2014, approximately 24 percent of Texas' population lived in one of these five cities.[50] I examined municipal per capita water use during a twenty-year period from 1993 to 2013, a time frame also chosen based on the availability of necessary data; the earliest water price data publicly available at this level dates from 1993.

For the purposes of this analysis, I included variables for per capita water use, water prices per 5,000 gallons, median household income, the number of weeks the county spent in drought during the year, the population density of the city, and the annual rainfall each city received. This was done to control for standard variables that influence water demand, including price, income, and weather, in order to estimate a water demand function that can highlight my variables of interest. I also included two interaction terms: one capturing the intersection of drought length and time, and another the intersection of drought length and population density. These interaction variables were included to capture variation in per person water demand due to the combined effects of drought, time, and population density. In order to determine the true relationship between population density and water use, I held each of these factors constant in various runs of my model.

The data are drawn from various sources. Per capita water use and population data for each year were drawn from the Texas Water Development Board's historical water use records. TWDB calculates this figure by dividing the net use allocated to a city by its population, divided by 365 days. Net use accounts for the water taken into a city, subtracting water sales to other systems or industrial users.[51] Water price data was taken from the Texas Municipal League's annual water and wastewater survey, and the first available responses were from 1993.[52] Municipalities completed the survey on a voluntary basis and although not every city responded every year, this data provides the best available historical glimpse of aggregated water rates. While compiling this dataset, in some cases nearby areas were used as an approximation of water prices. For instance, when San Antonio did not report a price in 1993, Alamo Heights was used as an approximate, as was Conroe for Houston in 1996, and so forth. Of the total 105 observations, 15 cases were approximated using nearby cities. Median household income was taken from 1990 and 2000 decennial Census data, using supplemental American Community Survey 1-year estimates beginning in the year 2005. Given the very different scale of the income observations in comparison to the other variables, these values were divided by a factor of 1000 for easier interpretation of the coefficient estimates. Population density was calculated based on land area square mileage provided by the Texas Office of the State Demographer.[53] Rainfall data was taken from NOAA monthly and annual historical rainfall summaries for Austin,[54] Dallas, [55] San Antonio, [56] El Paso,[57] and Houston,[58] and the number of weeks each city spent under drought conditions was taken from a database hosted by the United States Drought Monitor.[59] Summary statistics for these variables are offered in Table 3.

Rather than pooling all of this information, I combined each of these data points into a panel data set; this allowed me to combine time-series and cross-sectional data, observing each city in multiple years. The use of panel data in this case allowed me to control for unobserved factors at the city level not specifically included in the model (such as specific policies or water-saving technologies). I used a fixed-effects model for this purpose, exploiting only the variation within a city over time to identify my coefficients of interest. This also allowed me to better understand shifts in behavior of water users. I also included year fixed effects to control for economic growth, changes in state and federal water and water conservation policies, and other time-varying factors that may be common across cities.

Table 3: Variable Summary Statistics

Variable Name	**Definition**	**Abbreviation** (shown in Table 4)	**Mean Value**	**Standard Deviation**	**Min Value**	**Max Value**
Gallons Per Capita Per Day	Total municipal water use/city population	GPCD	169.79	37.08	119	303
Drought	Number of weeks the county spent in drought conditions during the year	DroughtWeeks	21.20	20.79	0	52
Population Density	Population/square mile in the city	Density	3035.58	453.15	2259.93	3892.1
Price	Cost per 5000 gallons	Price5KGal	13.63	4.59	5.90	28.18
Income	Median household income (divided by 1000)	MedianIncome	38.77	9.78	22.64	60.46
Time	Year (Covering 1993 to 2013, renamed 1 through 21)	Year	11	6.08	1	21
Rainfall	Inches per year	Rainfall	31.47	16.06	4.21	71.18
Drought & Time	Interaction between number of weeks in drought and the year	DroughtxTime	322.2	358.66	0	1,092
Drought & Population Density	Interaction between the number of weeks in drought and population density	DroughtxDensity	64,113.53	63,803.3	0	189,615.5

WATER DEMAND MODEL

$$w_{ct} = \beta_1 drought_{ct} + \beta_2 dens_{ct} + \beta_3 p_{ct} + \beta_4 I_{ct} + \beta_5 time_t + \beta_6 rain_{ct}$$
$$+ \beta_7 drought_{ct} * time_t + \beta_8 drought_{ct} * dens_{ct} + \alpha_c + \gamma_t + \epsilon_{ct}$$

The models estimated in this chapter are variations on the water demand equation above. The dependent variable, w_{ct}, is water demand in city c in year t, and the independent variables are as described in Table 3. I also control flexibly for unobservable city-level heterogeneity (factors that vary across cities, but not over time) using a city fixed effect (α_c), and for factors that vary by year, but not across cities using a year fixed effect (γ_t). The standard econometric error term is ε_{ct}.

STATEMENT OF HYPOTHESES

My formal null and alternative hypotheses for each of the independent variables are as follows:

Drought	H_0: β_1=0; H_A: β_1 <0
Population Density	H_0: β_2=0; H_A: β_2 >0
Price	H_0: β_3=0; H_A: β_3 <0
Income	H_0: β_4=0; H_A: β_4 >0
Time	H_0: β_5=0; H_A: β_5 <0
Rainfall	H_0: β_6=0; H_A: β_6 <0
Drought & Time	H_0: β_7=0; H_A: β_7 <0
Drought & Population Density	H_0: β_8=0; H_A: β_8 >0

I hypothesized that the following variables will have the greatest effect on water use (with my a priori assumptions of positive or negative relationships included):

- Length of Drought in weeks (-)

    - Hypothesis: as the number of weeks a city spent in drought increases, water use decreases
- Population density (+)
    - Hypothesis: as population density increases, water use increases
- Price of water (municipal water rate) (-)
    - Hypothesis: as water cost to the consumer increases, water use decreases
- Median household income level (+)
    - Hypothesis: as income increases, water use increases
- Year (-)
    - Hypothesis: as time increases, water use decreases due to greater efficiency
- Rainfall (-)
    - Hypothesis: as rainfall increases, water use decreases

I anticipated that as population density increases and areas become more urbanized, water use would increase due to a greater disconnect from the land and less awareness of the current conditions of water sources. I hypothesized that water rates, on the other hand, would likely see an inverse relationship to water use; as the price of water increases, I anticipated that consumers would decrease use. As median household income levels increase, I expected water use to increase; this is due to less incentive for cost reduction in cases where water costs are smaller portions of expenses for higher income families. I also expected that as time increases, water use would decrease due to greater water-saving efficiencies in toilets and other appliances. As rainfall totals increase, I anticipated that water use would decrease due to less water demand for irrigated lawns.

In some cases, I expected the impacts of different factors to vary based on circumstances; in other words, the marginal effects on per capita water use would be non-constant. I hypothesized that two interaction effects could be at work in this relationship:

- Interaction: drought and time (-)
    - I expected that as drought persists for greater lengths of time, the likelihood of a local government taking action to combat that drought would increase. This variable therefore served as a proxy measure to capture potential policy changes aimed at decreasing per capita water use. I expected the coefficient on this variable to be negative.
- Interaction: drought and population density (+)
    - I expected that the effect of drought on water use would be less pronounced in urban areas; though controlling for both population density and drought conditions already, I introduced an interaction term between the two to capture anticipated differences in more urban and more rural settings. The marginal impact on per capita water use for this variable reflects the combination of high drought and high density, and would show a pronounced impact when both variables have high values; as this variable increases, I expected water use to increase and the coefficient to be positive.

COMPARISON OF FOUR MODEL RESULTS

To gain an understanding of this relationship, I ran several different models and compared their results side by side. Each model was more restrictive than the last, holding constant more differences by city and year in the gallons per capita per day used. Table 4 reports these results.

Table 4: Comparison of Four Regression Models

	(1) GPCD	(2) GPCD	(3) GPCD	(4) GPCD
DroughtxDensity	0.000766+	-0.00000672	0.0000210	0.0000964
	(0.000402)	(0.000381)	(0.000370)	(0.000323)
Price5KGal	-5.359**	-2.419*	-1.512*	-1.361+
	(1.055)	(0.833)	(0.435)	(0.508)
Rainfall	-0.417	-0.663*	-0.693*	-0.696*
	(0.315)	(0.216)	(0.233)	(0.186)
DroughtWeeks	-2.198+	0.162	0.434	-0.852
	(1.195)	(0.972)	(1.212)	(0.478)
Density	0.0119	-0.0268+	-0.0200	-0.0281*
	(0.0136)	(0.0114)	(0.0140)	(0.00681)
MedianIncome	1.150+	0.0646	0.0435	0.547
	(0.660)	(0.488)	(0.734)	(0.676)
DroughtxTime			-0.0270	0.0435
			(0.0210)	(0.0441)
Year			-0.174	2.244
			(1.097)	(3.269)
_IYear2_2				-10.20
				(5.581)
_IYear2_3				-2.131
				(5.991)
_IYear2_4				0.677
				(20.34)
_IYear2_5				-16.20
				(29.50)
_IYear2_6				-17.81
				(25.49)
_IYear2_7				-26.26
				(30.22)
_IYear2_8				-40.45
				(39.79)
_IYear2_9				-58.65
				(43.45)
_IYear2_10				-61.35
				(67.66)
_IYear2_11				-90.71
				(67.06)
_cons	170.6**	298.4**	270.2**	272.2**
	(40.02)	(35.08)	(45.89)	(31.69)
N	78	78	78	78
R-sq	0.380	0.326	0.341	0.466
City FE	No	Yes	Yes	Yes
Year FE	No	No	No	Yes
Time Trend	No	No	Yes	Yes

Standard errors in parentheses
+ p<0.10, * p<0.05, ** p<0.01

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The first model (1) was a pooled ordinary least squares (OLS) regression. This model treated all data points as if they are uncorrelated by city or time. In other words, inter-group differences were not accounted for in this regression because all of the data are pooled together. At this level, my interaction term for drought and population density is significant, as well as the variables for weeks spent in drought, median income, and price. At this most basic level, it appears that there is a positive relationship between density, drought, and water use response; higher density areas spending lengthy periods in drought appear to use more water per person. Given that this is a panel data set, however, the model needs further specification to accurately portray the relationship; when treated as a regular regression, it is misspecified and the results are misleading.

The second model (2) included a fixed effect for each city. The use of a fixed effects model controlled for average water demand in a city (the portion of demand driven by characteristics constant in each city over time) and estimated the remaining effects of interest using only the variation in water demand within each city over time. This reduced the issue of underlying heterogeneity present in the model by accounting for unobserved differences between the cities that affect water use. At this stage, the variables that are significant change; price, rainfall, and density emerge as the three variables impacting per capita water use, and the interaction term for drought and density diminishes in importance.

The third model (3) included both city fixed effects and a time trend in the form of a variable for year, as well as the interaction term for drought and time. This captured an additional part of the relationship to water usage, shown in the slight increase in the model's R-squared value. In this model, price and rainfall again appear as significant factors in per capita water use.

The fourth model (4) was the most restrictive. It included city fixed effects, a time trend, and fixed effects for every two years. (The two-year interval was chosen to view trends in a more consolidated way than on an individual year basis and to allow enough remaining variation and degrees of freedom to estimate the coefficients of interest.) While none of the individual year effects are significant in model four, an F-test reveals that the full set of year effects is significant at 0.05 (the value of the F-statistic in the test for joint significance is 14.24, and the p-value is 0.0123).

This fourth model indicated that much of the relationship is actually captured and explained by the year fixed effects. For the bulk of these two-year periods, the relationship to gallons per capita per day is negative and the magnitudes generally increase (though not monotonically), indicating that water use generally trends down with each additional time period. This is consistent with national and state level trends for the decades observed in this analysis and is likely due to advancements in water saving technologies and appliances as well as policies emphasizing water conservation. Similar to previous models, variables for price, rainfall, and density appeared as significant factors, but the addition of year fixed effects highlights that time may be the major player in determining the outcome of per capita water use in these cities.

Overall, the price per 5,000 gallons of water, rainfall totals, and population density are significant on a fairly consistent basis. The lessened impact of the variables I intended to expose as the culprits driving changes in per capita water use is likely explained by the inclusion of the year fixed effects. Though I believe there is an underlying, nuanced relationship between drought, density, and per capita water use, this analysis didn't expose a strong one.

MODEL LIMITATIONS

This failure to expose a strong relationship between drought, density and water use may simply be a limitation of the type of data currently available. Many of the independent variables used in this analysis related to water use were derived from city or county-level totals. Although this information offered the best historical glimpse of the variables in question, it did not necessarily reflect direct water use behaviors on an individual basis. To truly understand the impact of population density on water use behavior, more nuanced data would be beneficial. As data collection becomes more sophisticated and on an ever-more individualized scale, it may become easier to expose this relationship. Current per capita water use is calculated in such a way that total municipal water use (total water use in a city for more purposes than just in the home) is divided by population totals. As data collection advances to better model water use per home, per person, or even per faucet in the home, understanding of how population density impacts this relationship can become more nuanced as well. Future analyses with more individualized data may be able to better expose this relationship, as well as what underlying factors influence different behavioral outcomes.

An additional confounding factor may simply be the involvement of municipalities in supplying water to city customers. In their role as suppliers, municipalities have the ability to dictate water prices, impacting consumer behavior in ways that are not necessarily easy to understand or to predict. In some cases, the municipal response to consumer behaviors is even more challenging to predict, even defying the regular laws of supply and demand. For instance, in cases when consumption of water goes down, rather than rewarding conservation by decreasing the costs to consumers, cities often actually raise water rates, to make up for the revenue shortfall caused by decreases in consumption due to conservation. This is done out of necessity to cover the costs of repairing and maintaining the expensive infrastructure responsible for delivering water to those consumers. In essence, using less water may not translate into lower prices for consumers, complicating the role of municipal delivery of water in urban settings.

Density, Drought, and Data

This analysis, though showing the presence of a relationship between density and water use in times of scarcity, barely scratches the surface of understanding that relationship. Water supply problems are certainly not unique to Texas municipalities. Meeting rising water demands from rapid population growth is an issue worldwide, and half of all cities with populations in excess of 100,000 are located in water scarce basins.[60] Because of this fact, further examination of changes in behavior related to water use could be a key step in establishing sustainable municipal water use. A study in the journal *Water Policy* highlighted trends in municipal water management to better understand potential policy solutions to municipal water issues in dry areas. The study demonstrated how municipalities in four water scarce areas (Adelaide, Australia; Phoenix, Arizona; San Antonio, Texas; and San Diego, California) dealt with scarcity in similar ways:

> The pattern begins with the exhaustion of local surface and groundwater supplies, continues with importation of water from other basins, and then turns to recycling of wastewater or storm water, or desalination of either seawater or brackish groundwater. Demand management through water conservation has mitigated, to varying degrees the timing of water-system expansions and the extent to which cities rely on new sources of supply.[61]

This study concludes that this development pattern is undesirable from a sustainability perspective, as it results in serious ecological and social impacts and is not cost-effective. Though it is helpful to understand the development of municipal water supply, these trends do little to increase an end-water-user's understanding of their individual impact on the problem. Perhaps this is the key issue in water scarcity: policy makers and planners observe macro-level trends and challenges, but have little ability to trace the source of those challenges to individual, micro-level users. Municipal water is not priced according to its value, or even its availability, complicating messages to consumers about the value of the resource. These are additional challenges to be met in future cases of drought.

RECOMMENDATION

To better understand the impact of population density on drought response, further study at the micro-level is needed. Until we understand individual behavioral responses based on a water consumer's urban or rural environment, we cannot plan for water supplies of the future in a nuanced fashion. If Texas' history of water use and drought response is any indication of future challenges, the time to focus on impacting water usage at the individual level is now.

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